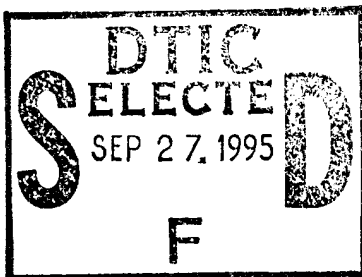


Bi-Monthly Progress Report
for
Real-time 3D Display Without Moving Parts

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1. Introduction

In our previous bi-monthly progress report (reporting period Oct.1, 1994 - Nov.30, 1994) we reported the accomplishments on (1) performance comparison of two different operational modes using photorefractive materials, (2) performance comparison of using different photorefractive materials, and (3) HOE array design for dynamic image. The simulation results indicated that real-time mode of operation combining with BSO crystal offers the best performance. During the last two months we focused our efforts on the following 5 items:

- (1) Fabricate the HOE array that was designed previously and demonstrate a dynamic imaging system using the HOE array.
- (2) Investigate different 3D visualization data rendering software that are commercially available and find out which are suitable for our display system.
- (3) Investigate a new 3D display scheme that uses two counter-propagating pulses collision and compare it with the orthogonal illumination scheme.
- (4) Investigate the performance of using 2-photon 3D material and compare it with photorefractive materials.
- (5) Preliminary design of a prototype 3D display system

The results are summarized in Section 2 and detailed report of the accomplishment is presented in Section 3.

2. Summary of the Accomplishments in the Second Two-Month

The accomplishments for the second two months of Phase-I can be summarized into the following four parts:

- Demonstration of a dynamic imaging system using an HOE array. Several HOE arrays (3x3) (the size of each element on the array is 1mm x 1mm) have been fabricated, and the novel approach of dynamic focusing using these HOE arrays was successfully demonstrated with a dynamic range larger than 10 cm and high image quality.
- 3D visualization data rendering software for our system. We have investigated many different 3D visualization data rendering software and consulted experts of 3D visualization at San Diego Super Computer Center, and found out that there are several commercially available software can be used directly for our 3D display system. We have obtained a copy of *Xdataslice* from University of Illinois at Urbana-Champaign.
- Feasibility study. We have carried out the feasibility study on two different information access schemes, namely orthogonal illumination and counter-propagating pulses collision.

We have also performed the feasibility study on two different materials, namely photorefractive crystal and 2-photon 3D material. The simulation result on scheme feasibility study indicates that the performance of counter-propagating pulses collision will be better than orthogonal illumination when pulse width is shorter than 1 ps for a 10 cm display cube and 3 ps for a 100 cm display cube. The simulation result on material feasibility study indicates that 2-photon material with up conversion efficiency larger than 10^{-2} can support a voxel bandwidth larger than 3×10^{10} at 100 mW optical power and 3×10^{12} at 10W optical power, which is 2 orders of magnitude higher than photorefractive materials can offer.

• Preliminary Prototype 3D display system design. Based on the results of feasibility study obtained during the first and second two-month, we have carried out a preliminary prototype 3D display system design that employs 2-photon materials and counter-propagating pulses collision. The design involves three unique features: dynamic imaging, highly accurate time delay pulse collision and compact system.

More details about the accomplishment for the second two-month are given in Section 3.

3. Accomplishment

3.1. HOE Array Fabrication and Experimental Demonstration of A Dynamic Image System

Dynamic focusing is required to image the 2D cross sectional images at different desired depths inside display material (see Fig.1). This will be achieved by adding an array

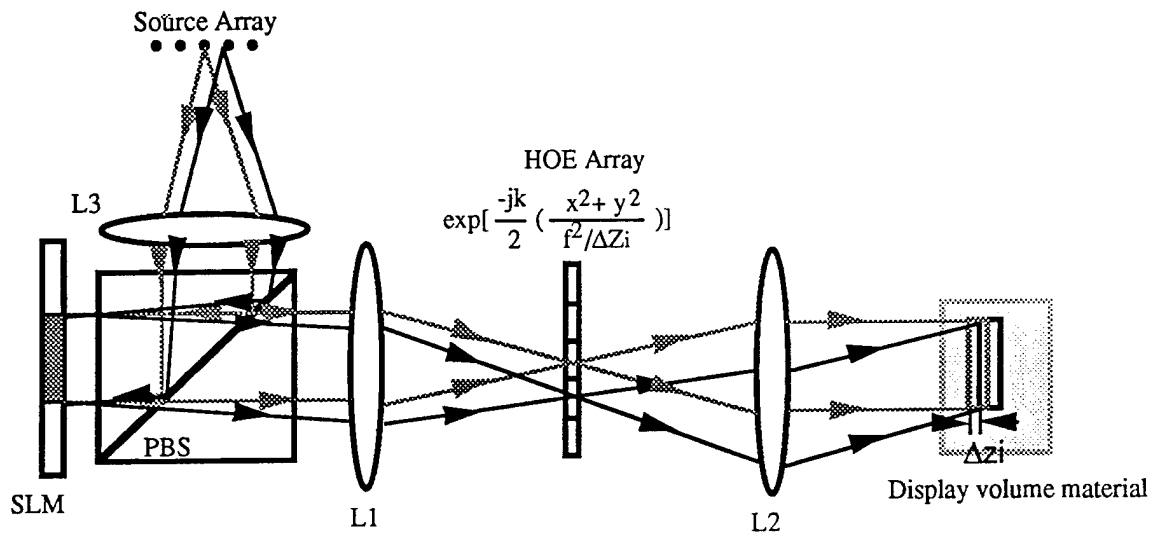


Fig.1 Schematic diagram of a dynamic image system. Illumination of the SLM with different light source in the source array selects different element in the HOE array, resulting in different focused imaging distances.

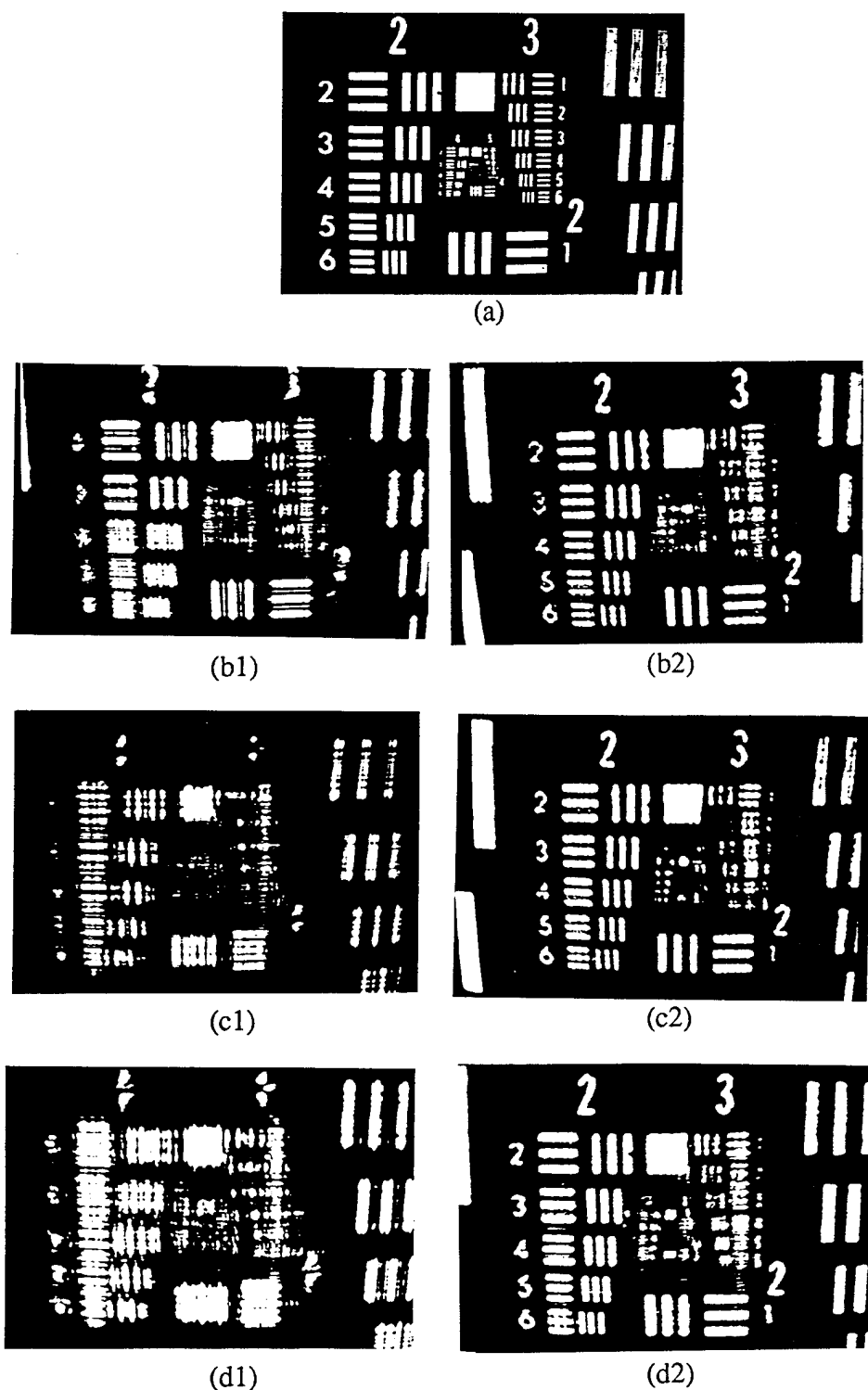


Fig.2. Experimental result of dynamic focusing. (a) Camera at the original reference plane $\Delta z_i = 0$; (b1) Camera at $\Delta z_i = 2\text{cm}$ without using HOE ; (b2) Camera at $\Delta z_i = 2\text{cm}$ with HOE; (c1) Camera at $\Delta z_i = -5\text{ cm}$ without using HOE ; (c2) Camera at $\Delta z_i = -5\text{cm}$ with HOE; (d1) Camera at $\Delta z_i = 5.5\text{ cm}$ without using HOE ; (d2) Camera at $\Delta z_i = 5.5\text{ cm}$ with HOE.

of HOEs into a conventional 4f image system. Each element in the HOE array provides a quadratic phase to shift the focused image a distance Δz_i from the reference image plane. Different HOE in the array can be selected by illuminating the SLM with different light source in a source array (or plane wave of different angles). Several HOE arrays have been designed using commercial optical design software CODE-V to eliminate the aberrations caused by off-axis and the result was reported in our previous report. Several HOE arrays of array size 3 x 3 with 1mm x 1mm size of each element on the array were fabricated using e-beam direct write and chemically assisted ion beam etching technique. These HOE arrays were inserted in a 4f image system similar to that shown Fig.1, and its capability of dynamic focusing was successfully demonstrated. Fig.2 shows the pictures of part of the experimental result. Image dynamic focusing range of more than 10 cm were achieved.

3.2. 3D Visualization Data Rendering Software Suitable for Our System

During the last two months we have investigated the availability of 3D visualization data rendering software that is suitable for our particular display applications. By consulting with the 3D visualization experts at San Diego Super Computer Center, we found that there are several commercial software that displays 3D data in the format of many slices, such as *Xdataslice* made by and University of Illinois at Urbana-Champaign and *Dicer* made by Spyglass Inc.. These software can be used directly to our system. We have obtained a copy of *Xdataslice* which can be run on most of the Xwindow devices. We plan to test it on Sun WorkStation during the next two months.

3.3 Performance Comparison of Counter-Propagating Pulses Collision and Orthogonal Illumination for 3D Display

A feasibility study of comparing two 3D display schemes, namely orthogonal illumination scheme and counter-propagating pulses collision scheme has been carried during the second two-month. The principle of orthogonal illumination scheme (shown in Fig.3) has been presented in our previous report. The principle of counter-propagating pulse collision for 3D display is described in Fig.4. A sectional image is generated inside a 3D material by overlapping two counter-propagating pulses (one carrying a sectional image and another carrying a plane wave). A 3D image is composed through colliding a series of 2D sectional images focused at different depths with a series of plane waves. This is achieved by combining dynamic focusing with time delay pulse collision. Dynamic focusing is achieved by inserting an HOE array into a 4f image system as shown in Fig.1, and time delay pulse collision is achieved by controlling the time delay between pulses of the plane waves as shown in Fig.5. Although both photorefractive and 2-photon materials can be used in this scheme, 2-photon material is more attractive owing to its fast displaying speed and high signal to noise ratio in displayed images (see Section 3.4).

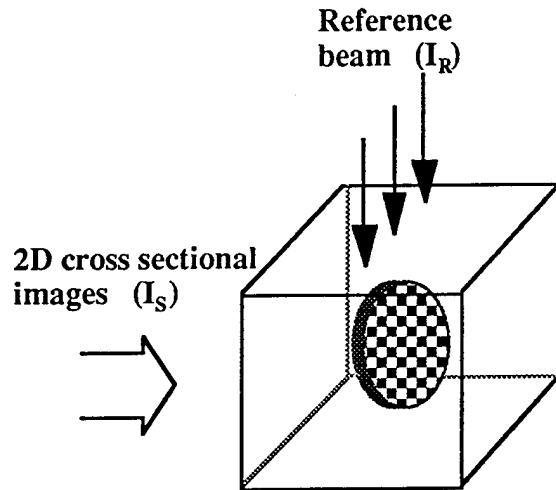


Fig.3. 3D display using orthogonal illumination scheme.

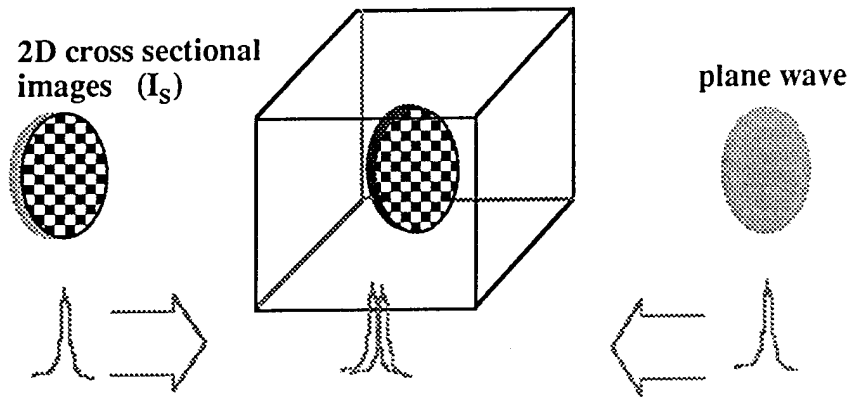


Fig.4. 3D display using counter-propagating pulses collision.

When using 2-photon material, the two counter-propagating pulses are invisible (at near infrared wavelength); the overlapping of the two pulses gives rise to the fluorescence in visible via 2-photon absorption and re-emission (see Section 3.4 for more details).

Comparing to orthogonal illumination scheme, counter-propagating pulses collision possesses the advantage of higher resolution in displaying depth. In the orthogonal illumination scheme, the display resolution in depth (z direction) is limited by the diffraction-limited beam size (see Fig.6). If L is the edge of the cube, the Gaussian beam with the smallest width at the top and the bottom of the displaying material cube is $(L\lambda/\pi)^{1/2}$ and a minimum size at the center smaller by a factor of $2^{1/2}$. In the counter-propagating pulses collision scheme, the resolution is determined by the pulse width $\Delta\tau$ through $\Delta\tau v$, where v is the speed of light in the material. Fig.7 shows that counter-propagating pulses collision scheme offers higher resolution when $\Delta\tau < 1\text{ps}$ for $L = 10\text{ cm}$, and $\Delta\tau < 3\text{ps}$ for $L = 100\text{ cm}$.

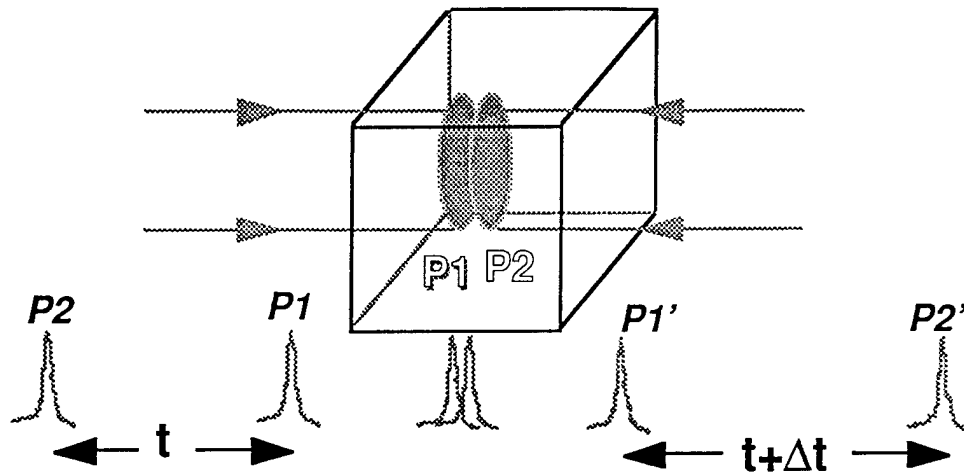


Fig. 5. Time delay pulse collision for display sectional images at different depths inside a 3D material. Pulse $P1$ collides with pulse $P1'$ at location $P1$; pulse $P2$ collides with pulse $P2'$ at location $P2$.

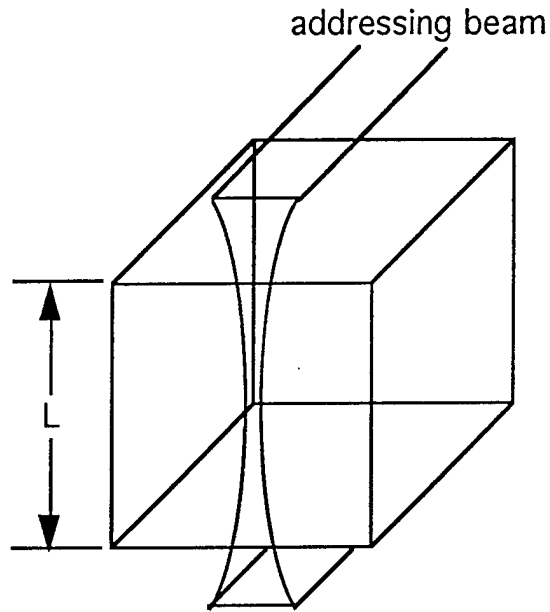


Fig.6. The shape of the addressing beam in orthogonal illumination scheme.

One critical issue related to pulse collision scheme is how to control time delay accurately so that pulse collision will appear in the desired location. This problem is still under investigation and one possible solution is presented in Section 3.5.

3.4. Performance Comparison of 2-photon and Photorefractive Materials

It is concluded in our previous report that if using photorefractive materials for 3D display, BSO is the best candidate. In the following we will report the result of comparing photorefractive materials (BSO) with 2-photon material for 3D display application.

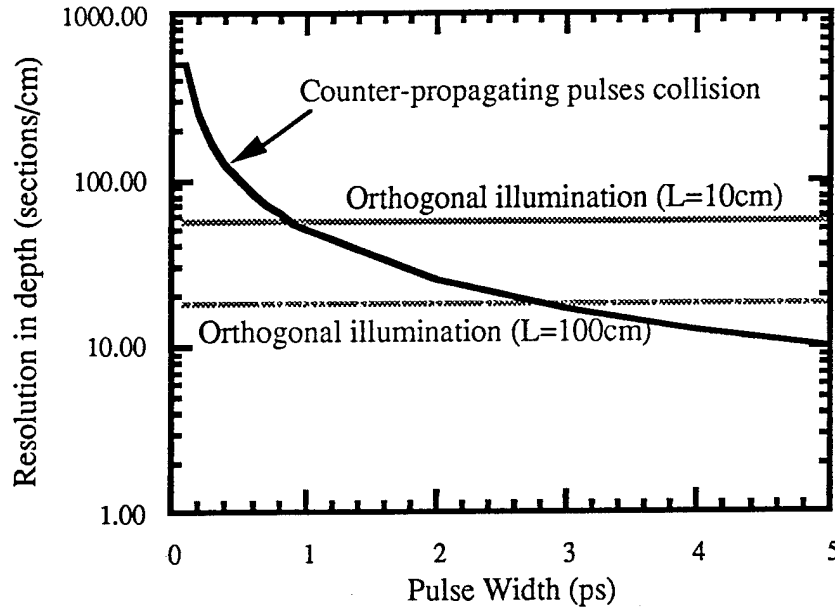


Fig.7. Comparison of 3D display resolution in depth for two different schemes: Orthogonal illumination and counter-propagating pulse collision.

The concept of using 2-photon materials for 3D display is easily understood by reference to Fig.8. Fig.8 depicts a simplified atomic or molecular energy level diagram for a material having a ground state (1) and two excited states (2) and (3). State (2) can be either a real state or a virtual state depending on the material. However, for avoid "ghost" image in fast 3D display, virtual state (2) is preferred. The material is chosen so that by absorbing 2 infrared photons, visible fluorescence is emitted as a result of decay from level (3) to the ground. Its immediate advantage is high signal to noise ratio comparing to photorefractive material. In the case of using photorefractive crystal, the readout image lies in a strong reading (or reference) beam background because both reading and readout beams are visible, resulting in a poor signal to noise ratio. However, in the case of using 2-photon material, the two counter-propagating pulses are invisible. As a result of 2-photon process, only an isolated fluorescent section can be seen in the overlapping region, yielding an extremely high signal to noise ratio.

Besides signal to noise ratio, we have chosen voxel bandwidth (number of voxels displayed per second) as a figure of merit for comparison. Let W be the input optical power, Δt be the time used for recording/displaying each sectional image, p be the required power for each voxel for comfortable viewing, the voxel bandwidth B can be expressed in general by

$$B = \frac{W \eta}{30 p \Delta t},$$

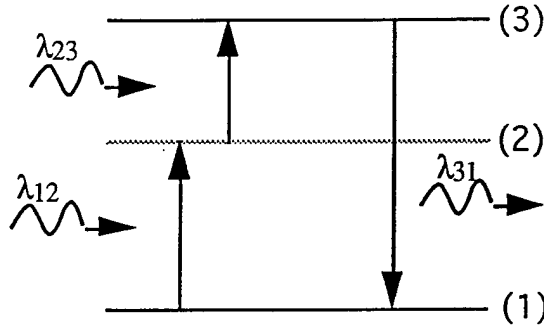


Fig.8. Energy-level diagram for 2-photon absorption and upconversion fluorescence.

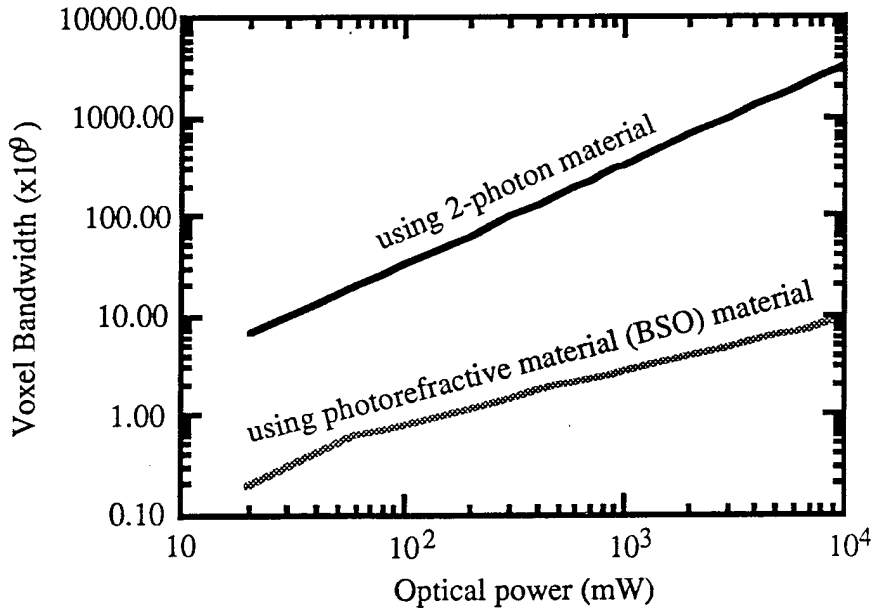


Fig.9 Comparison of 3D display voxel bandwidth for using photorefractive material (BSO) and 2-photon material.

where η is the diffraction efficiency for photorefractive material or 2-photon up conversion efficiency (or fluorescence quantum yield) for 2-photon materials. For photorefractive material, η and Δt are strongly interrelated; usually larger the η longer the Δt . However, for 2-photon material, the number of excited state (3) saturates very quickly (~ 100 ps to a few ns). Therefore, η and Δt is independent so long as Δt being long enough to saturate state (3). The value of η is material dependent, ranging from 10^{-6} of $\text{CaF}_2:\text{Er}^{+3}$ to 10^{-2} of poly-2-hydroxyethyl methacrylate. Fig.9 shows the comparison of B by using photorefractive BSO crystal and 2-photon material; where $\eta = 10^{-2}$ and $\Delta t = 1$ ns were used for the simulation of 2-photon material. $p = 10^{-7}$ Watt was used in the calculation of Fig.9, which has been shown adequately for comfortable viewing in a dimly lit room. 2-

photon material demonstrated much higher voxel bandwidth (3×10^{10} at 100 mW optical power and 3×10^{12} at 10W optical power) than photorefractive can achieve.

3.5. Preliminary Design Of A Prototype 3D Display System

Based on the feasibility study of various different options in the present and the previous reports, we concluded that counter-propagating pulses collision scheme together with the use of 2-photon material offers the best performance for a real-time true 3D display. A preliminary design of a prototype 3D display system has been carried out during the last two months, and the result are given in the following.

The principle of the prototype design for real-time 3D display is described in Fig.10. A 3D image is composed from a series of 2D cross sectional images focused at different depths. Sectional images are generated sequentially in real-time inside a 3D material by overlapping two counter propagating IR pulses (one carrying a sectional image information and another carrying a plane wave of various time delays) at different depths. A SLM is used to display the 2D image series sequentially and a Holographic Optical Element (HOE) in an HOE array shifts the images to different desired focal distances. (Each element in the HOE array provides a quadratic phase function with a radius of curvature of $f^2/\Delta z_i$, which shifts the focused image a distance Δz_i from a reference image plane.) Different HOE in the array can be selected by illuminating the SLM with different light source in a source array.

The first novel feature of our approach is dynamic focusing that uses an HOE array in a conventional $4f$ image system, which has been demonstrated successfully recently (see Section 3.1). A spatial light modulator (SLM) displays a sectional image and one of the holographic optical element (HOE) in a HOE array helps to focus the image at a desired depth inside the 2-photon 3D material. (Each element in the HOE array provides a quadratic phase with a radius of curvature of $f^2/\Delta z_i$, which shifts the focused image a distance Δz_i from the reference image plane determined by the refractive lens.) Illumination of the SLM from a different micro-laser in the laser array helps to select a different HOE in the HOE array, resulting in a different imaging distance. The speed of random displaying different image sections is solely determined by the speed of switching between different micro-lasers in the laser arrays, or the frame rate of the SLM. Microlasers can be switched at nano-sec speed and PLZT SLM can be operated at tens to hundreds MHz frame-rate. The achievable number of the memory planes is determined by the number of HOE elements in the HOE array. A CGH of $1\text{mm} \times 1\text{mm}$ can support a throughput larger than 10^6 bits. A 32×32 array (size $32\text{mm} \times 32\text{mm}$) allows us to have 1024 dynamically focused planes.

The next novel feature of our approach is a time delayed pulse collision scheme from two injection locked, mode locked lasers. The principle of the approach is illustrated in Figs.12 and 13. Each sectional image is displayed by overlapping (collision) two counter propagating pulses from two pulse trains, one carrying the information displayed on the SLM and another carrying a plane wave. These

two pulse trains can be generated from two mode-locked micro-laser arrays, injection-locked by a master mode-locked laser together with a Dammann grating; the master laser and the Dammann grating generate an array of beams, as illustrated in Fig.12, to ensure time synchronization of the pulse trains (see Fig.13). The relative time delay between one pulse train with respect of the other determines the location of pulse collision and the desired memory layer to store the information. Incremental time delays among different microlasers in array #2 are provided by incremental length differences of fibers between the master micro-laser and the micro-lasers in array #2. For example, pulse train 0 collides with pulse train 1 at location P1; pulse train 0 collides with pulse train 2 at location P2; and so on. The incremental change in depth is $(\Delta t)v$, where v is the speed of light in the 2-photon material. For achieving a section layer thickness of smaller than $50\text{ }\mu\text{m}$ and collision location accuracy of better than $10\text{ }\mu\text{m}$, it is required that the pulse width smaller than 125fs and incremental time delay $\Delta t \sim 250\text{fs}$ with an accuracy of better than 25fs. This corresponds to $50\text{ }\mu\text{m} \pm 10\text{ }\mu\text{m}$ incremental length of fiber and allows 1024 sectional images to be displayed in a volume of 5cm in depth. This scheme is allow to display 3D images of 1024×1024 pixels per frames and 1024 frames in depth inside a $(5\text{cm})^3$ volume medium at 30 times/sec. (voxel bandwidth $> 3 \times 10^{10}$).

Finally, advantages of compactness and low cost are realized by using laser diode array (instead of expensive and large size Argon or Ti-sapphire lasers), fiber delay lines (instead of other complicated pulse delay scheme involving expensive acousto-optic deflectors), and HOE array. It would be much easier to package this dynamic focusing scheme than other schemes for compactness.

Detailed design is under way and the result will be presented in our next report.

4. Looking Ahead

In the next two months we will emphasize on the following tasks: (1) A final prototype 3D display system design. (2) Testing of using dynamic focusing HOE array combining with Quantex's 3D IR sensor cube for a real-time 3D display. (3) Testing the suitability of a 3D data rendering software *Xdataslice* for our particular display prototype. (4) Line up users and commercial partners.

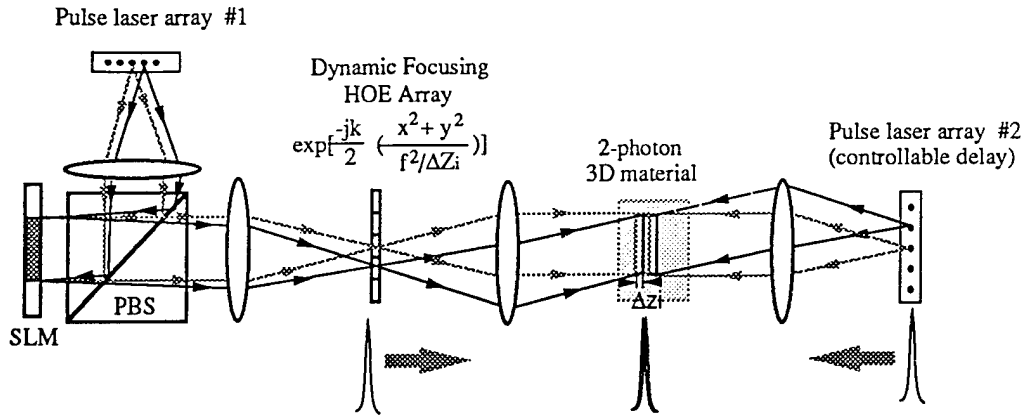


Fig.10. A preliminary design of a real-time 3D display that employs dynamic focusing and counter-propagating pulses collision. Dynamic focusing is realized by illuminating the SLM that displays sectional images with a different micro-laser in the laser array #1 which selects also a different HOE in the HOE array, resulting in different imaging location inside the 2-photon 3D material. The 2D sectional image is generated via 2-photon fluorescence at the collision location of two counter propagation pulses from pulse trains with different relative delay times from two injection locked, mode locked laser arrays.

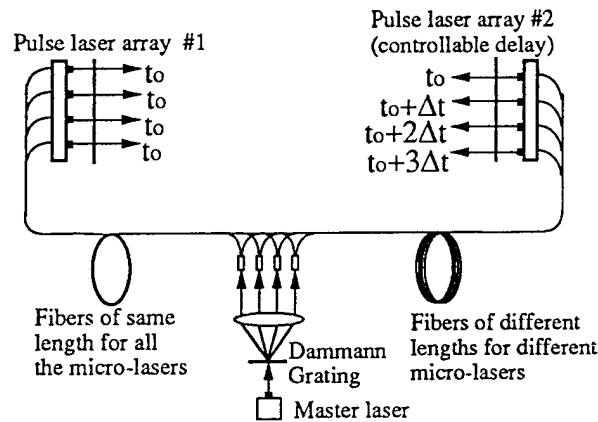


Fig.12. Injection locking of two mode-locked micro-laser arrays using a master laser through a Dammann grating and fibers. Time delays in pulses from micro-laser array #2 are controlled by different fiber lengths.

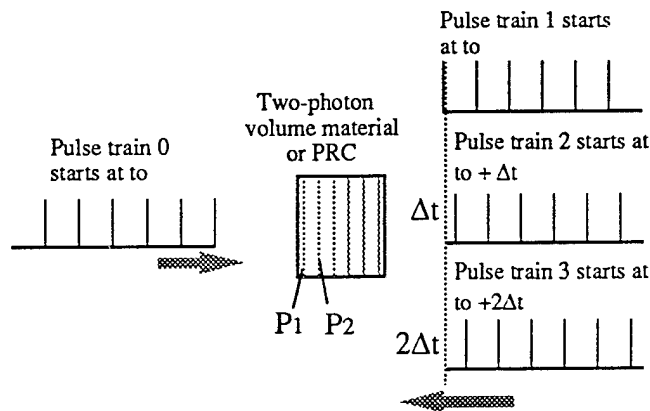


Fig.13. Schematic diagram of pulse collision at different depths of the 3D material by colliding two counter propagating pulse trains of different relative time delays.